Coherent Synchrotron Radiation studies at the A0 photoinjector

Jayakar Charles Tobin Thangaraj
& the A0 team

Outline of the talk

Introduction

Coherent Synchrotron Radiation

- Detection and characterization of radiation
- Studies on the electron beam
- Impact on accelerator operation

Conclusions

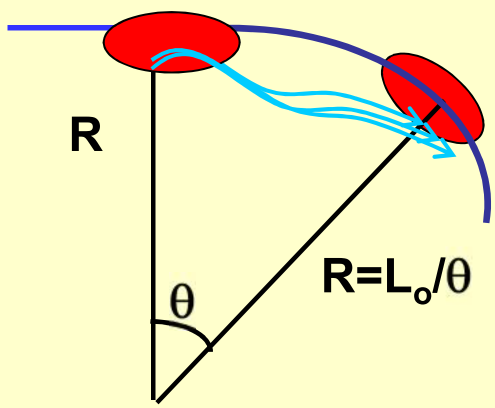
Coherent Synchrotron Radiation

- Synchrotron radiation is the result of individual electrons that randomly emit photons when passing through a bending magnet.

- Coherent synchrotron radiation (CSR) is produced when a group of electrons collectively emit photons in phase. This occurs when bunch length is shorter than radiation wavelength.

Why is it important?

- CSR induces an energy redistribution along the bunch.



Coherent radiation for $\lambda_r > \sigma_z$

- This energy modulation inside the dipole may result in modulation of the transverse slopes which may increase the projected emittance in the bend plane

Condition for coherent radiation

$$P(\lambda) = p(\lambda) N_e [1 + (N_e - 1) f(\lambda)]$$

$P(\lambda)$ Total power radiated at wavelength λ

$p(\lambda)$ Synchrotron radiation from one electron

N_e Number of electrons in the bunch

$f(\lambda) = 1$ for $\lambda >> \sigma_l$

CSR effect on the bunch is….

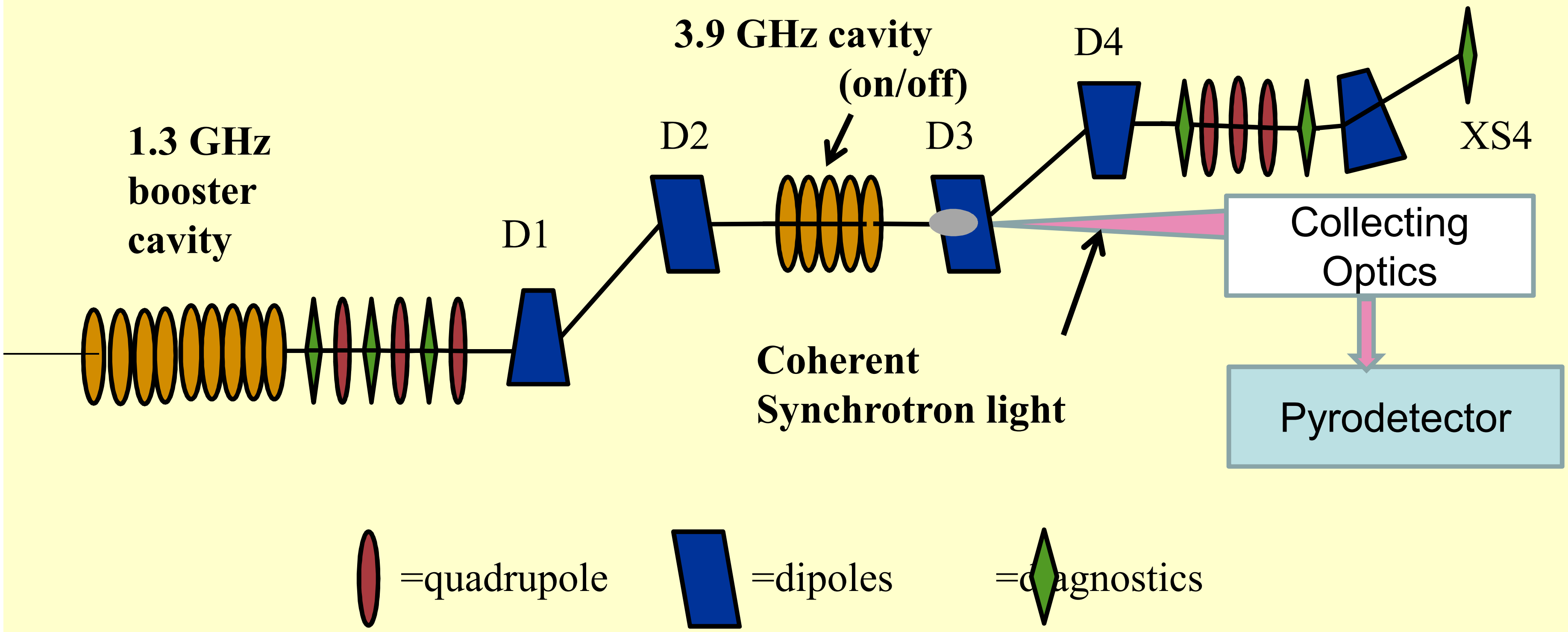
$$\frac{\varepsilon}{\varepsilon_0} = \sqrt{1 + \frac{\beta(\frac{L_B}{\rho}\frac{\sigma_\gamma}{\gamma})^2}{\varepsilon_0}}$$

ε emittance growth due to CSR (bend plane)

$\frac{\sigma_\gamma}{\gamma}$ energy spread induced through CSR

Particles get deflected differently due to the energy spread induced by CSR leading to an angular spread which shows up as emittance growth

The A0 beamline



Long wavelength cutoff due to vacuum chamber

$$\lambda_{cutoff} = 2h\sqrt{\frac{h}{\rho}}$$

h Height of the chamber 1.8 inches

ρ Bending radius 900 mm

λ_{cutoff} 20mm

CSR effect on the bunch is….

$$\Delta E = 0.35mc^2 \frac{N_e r_e L_B}{(\rho\sigma_z^2)^{2/3}}$$

r_e Classical electron radius

L_B Length of the bend

N_e Number of *electrons* in the bunch

CSR : Measurements

- Power
- Polarization
- Angular Distribution
- Using CSR as a bunchlength monitor

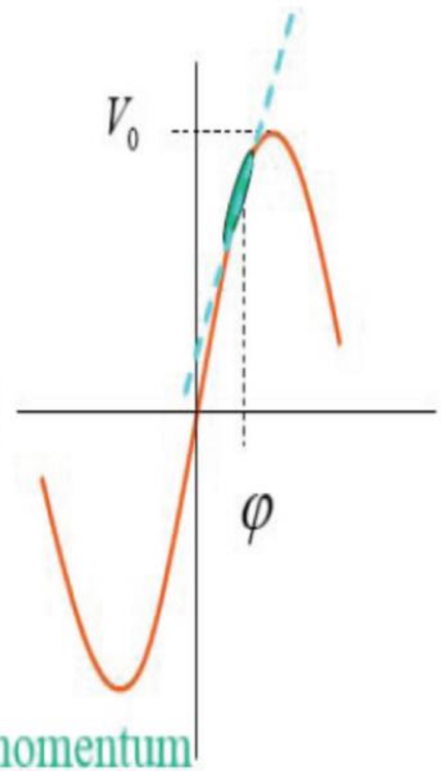
What to expect ? Some estimates…

- Energy time correlation:

$$E(z) = E_0 + eV_0 \cos(kz + \varphi)$$

$$\delta = \frac{eV_0}{E_0 + eV_0 \cos\varphi}\left[\cos(kz+\varphi) - \cos\varphi\right] = \kappa z + O(z^2)$$

chirp: $\kappa \equiv \frac{d\delta}{dz} = \frac{-keV_0}{E_0 + eV_0 \cos\varphi} \sin\varphi$



- Bunch compressor

1st order momentum compaction

$$z_f = z_i + R_{56}\delta_i$$

Chirp maths:

$$\sigma_{z,f} = \sqrt{(1+\kappa R_{56})^2 \sigma_{z,i}^2 + R_{56}^2 \sigma_{\delta_i}^2}$$

For minimum bunch length

$$\kappa = -\frac{1}{R_{56}} = 8.33; R_{56} = 0.12 \quad \text{This yields} \quad \varphi = 23^0$$

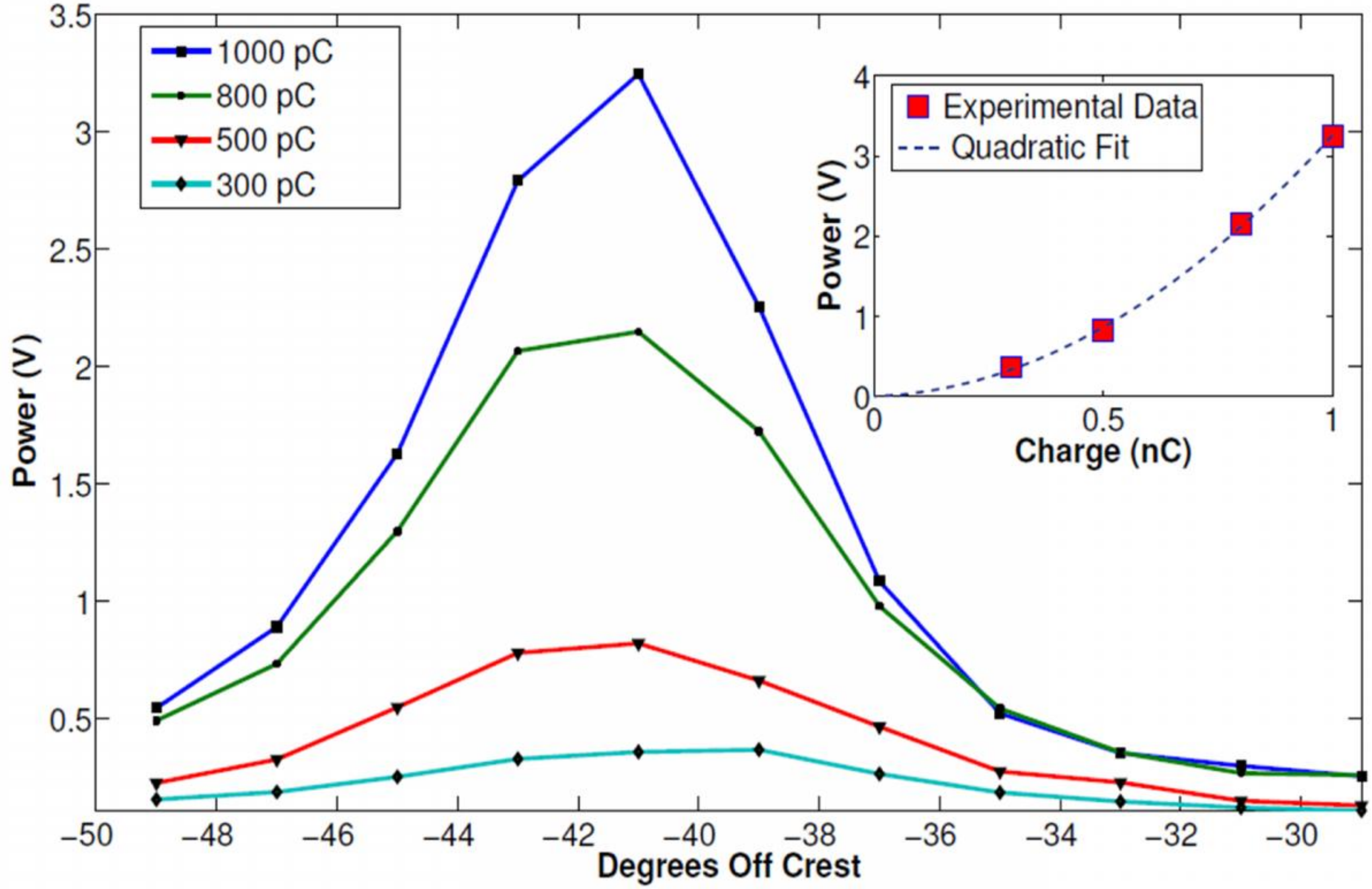
For minimum energy spread: $\varphi_{\min} = 25^0$ [Nominal operation]

Therefore total chirp on the beam for minimum bunch length .

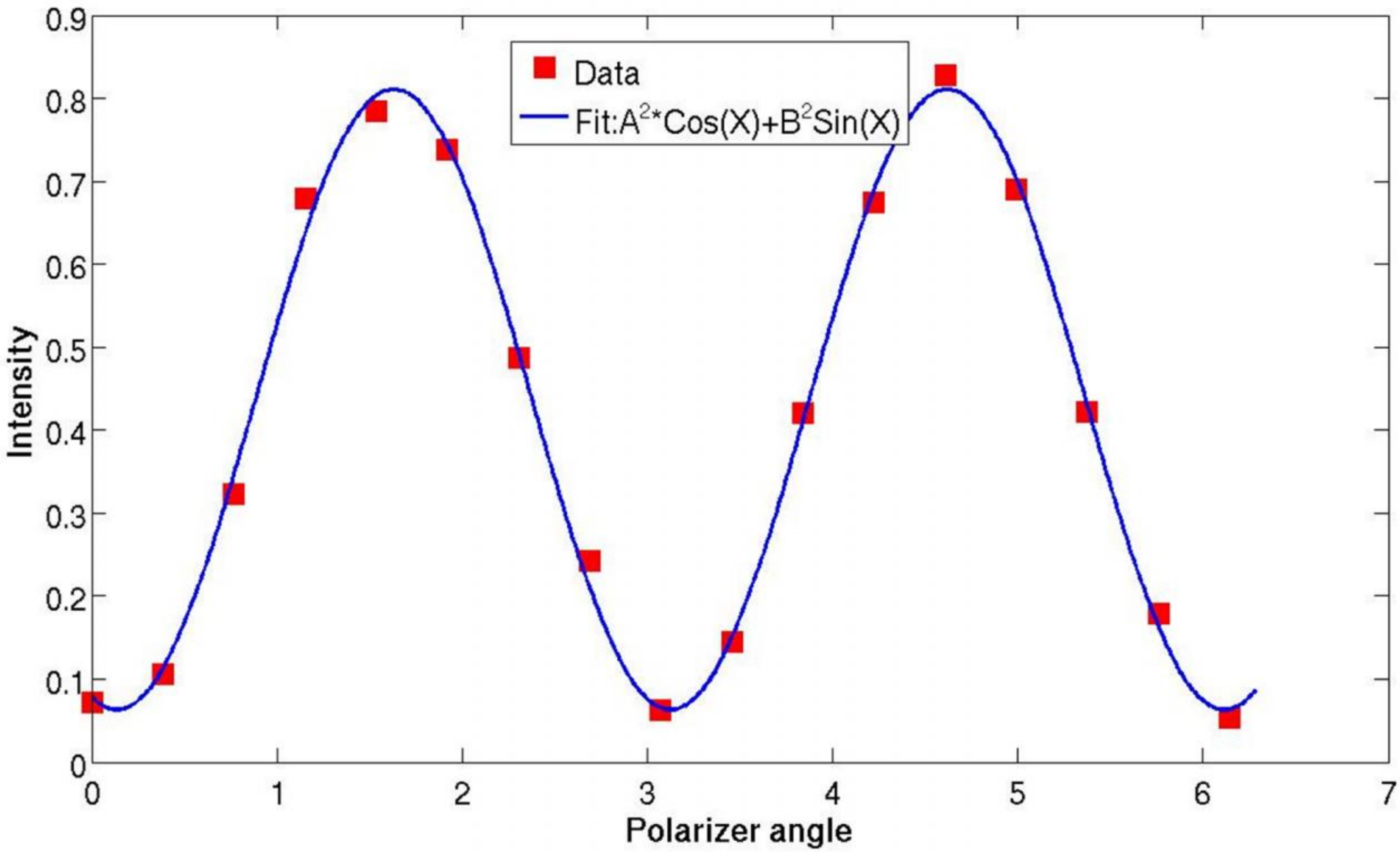
corresponds to $\varphi \sim 38^0 - 42^0$

- We expect maximum CSR power around 40 deg off crest.

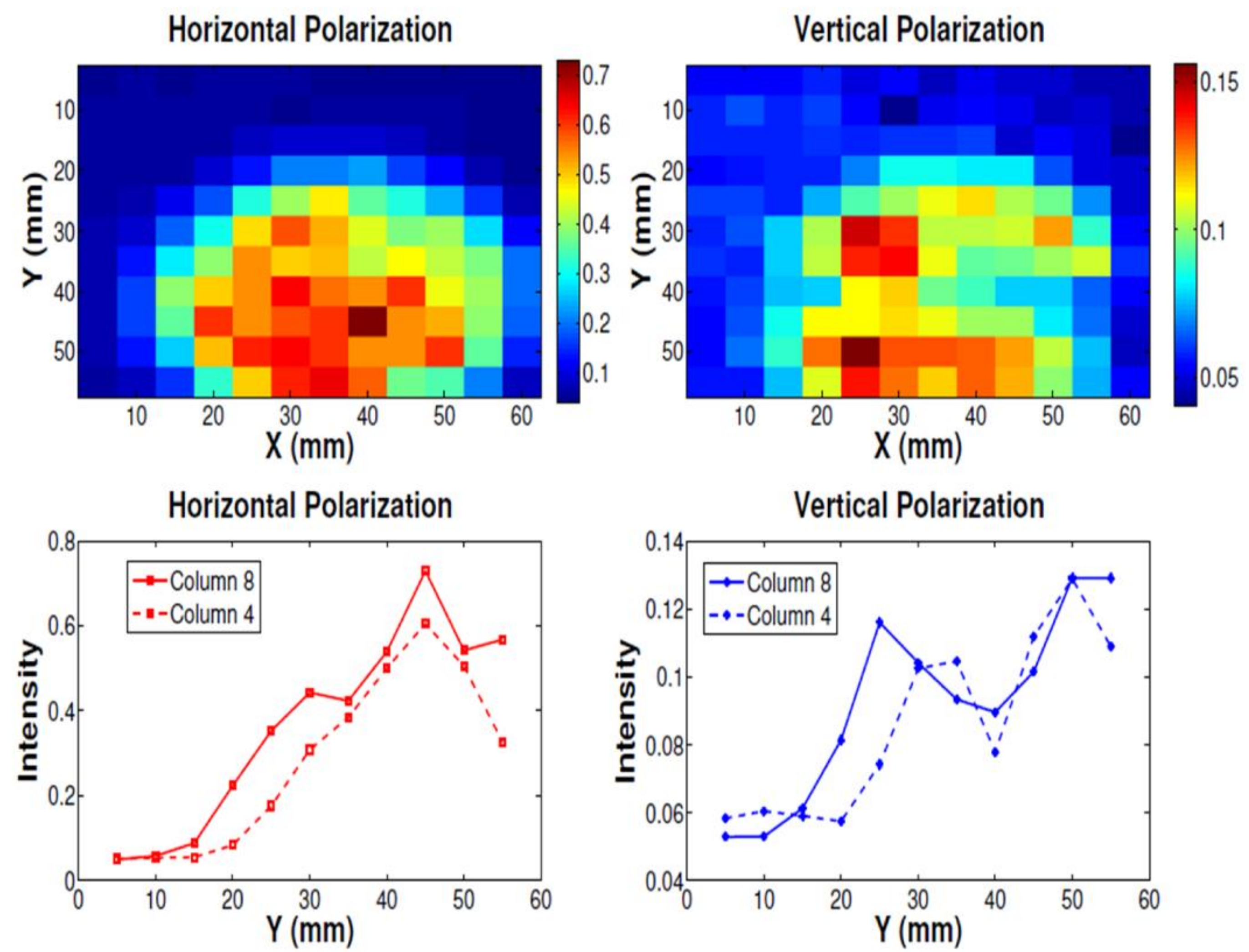
CSR Power Vs RF Phase (bunchlength)



Polarizer angle vs CSR

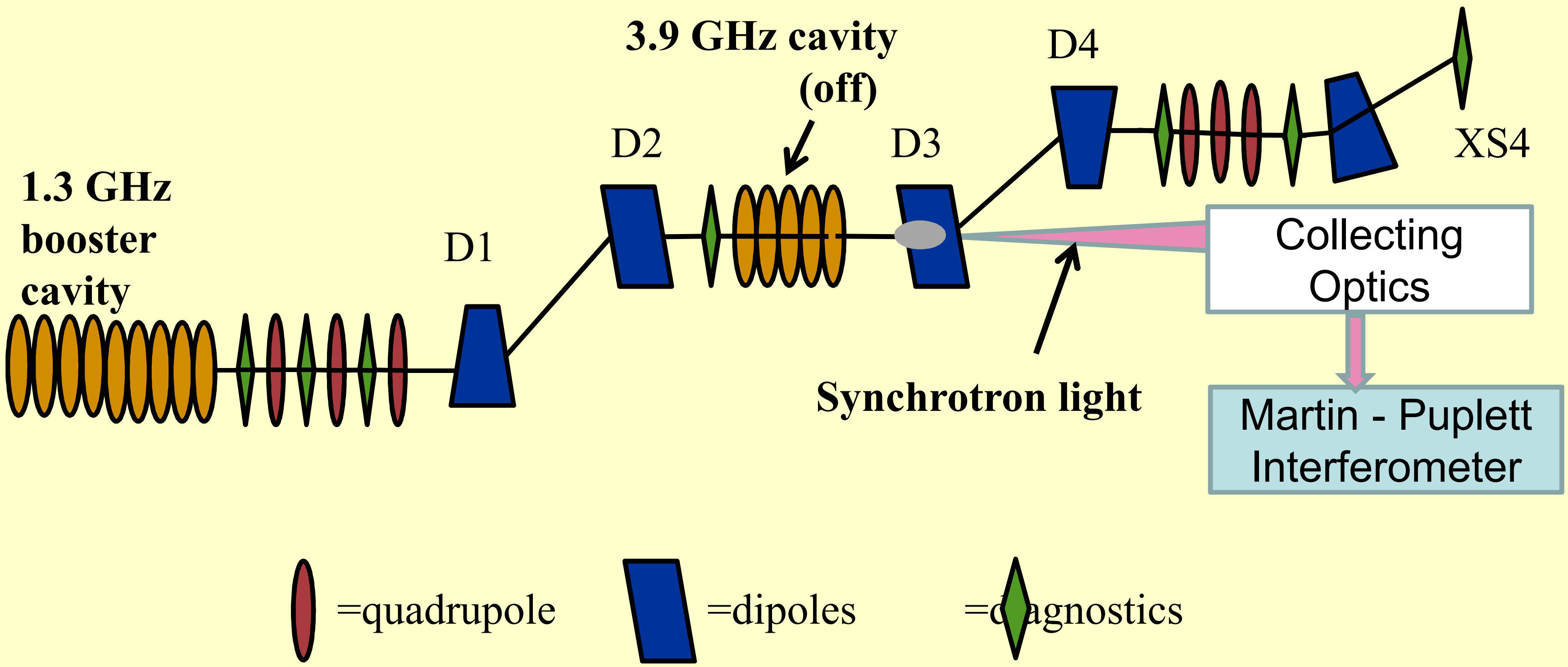


CSR Angular distribution

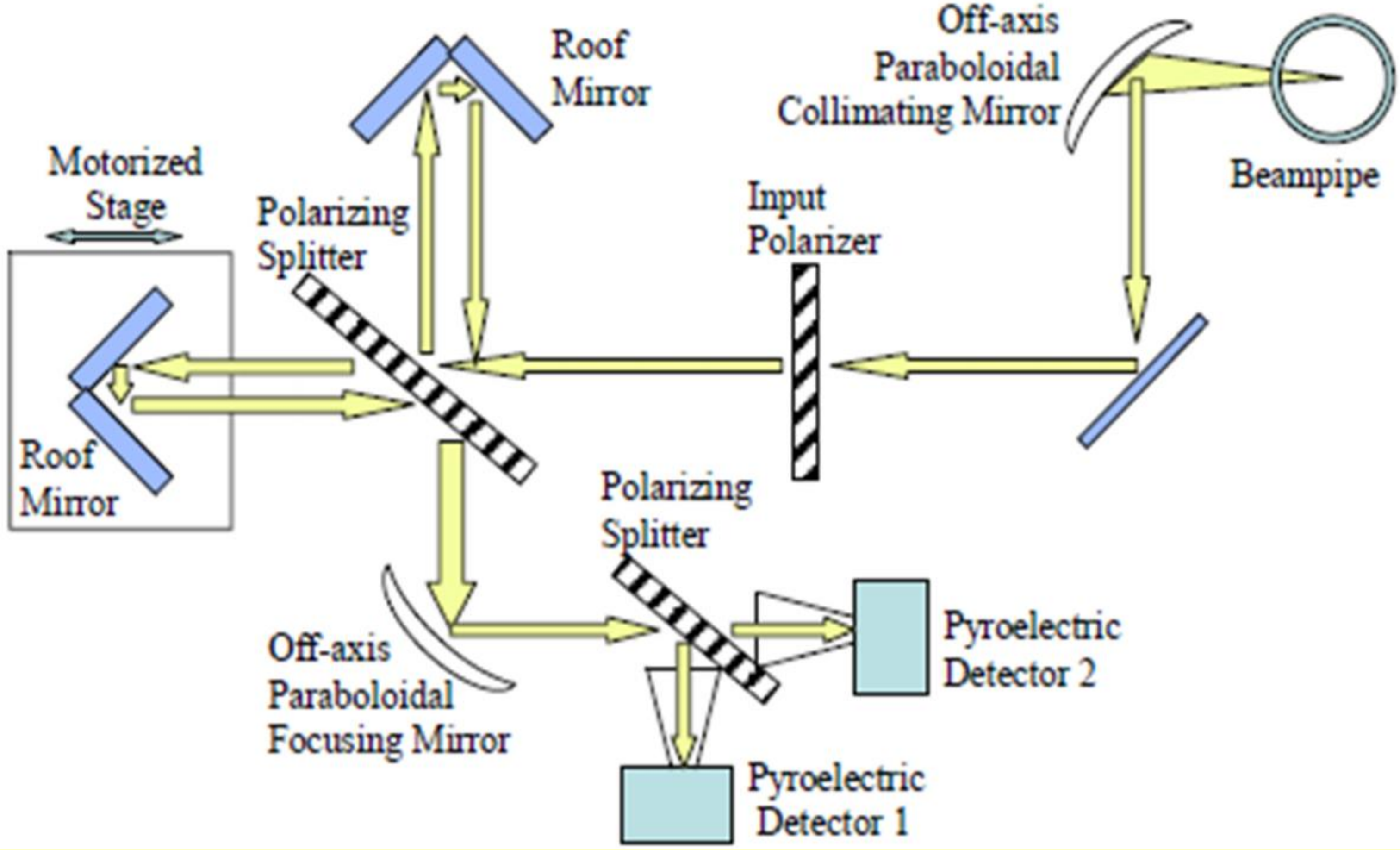


Ratio (Horizontal to vertical) = 4.6

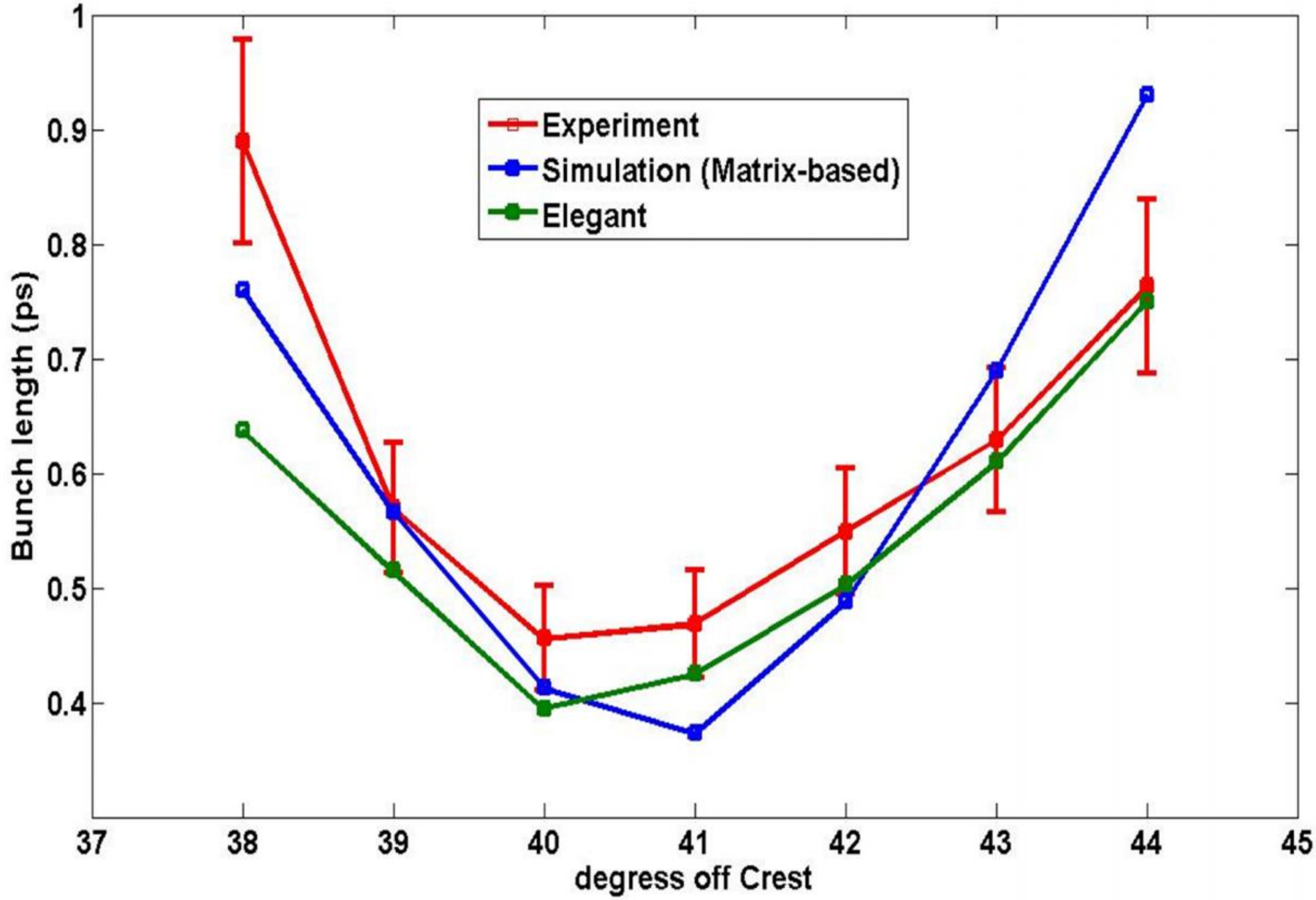
Bunch length measurement: Experimental Setup



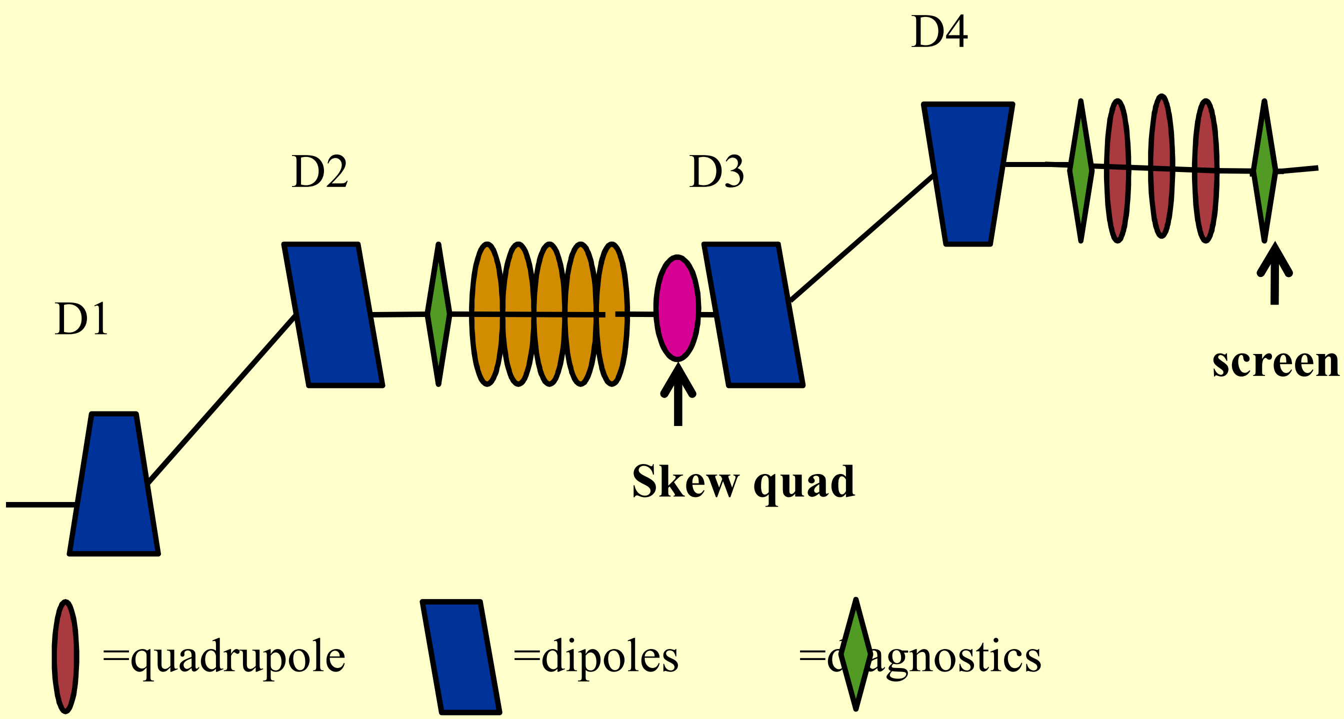
Martin – Puplett interferometer



Bunch length measurement: Simulation Vs Experiment



Studying the effects of CSR on the beam



“Skewed” maths

$$\boxed{\sigma_{quad} = \sqrt{\beta_{quad}\varepsilon_x + (\eta_x\delta)^2}}$$

$$\eta_x = \text{Horizontal dispersion at the quad}$$

$$\beta_{quad} = \text{Beta function at the quad}$$

$$\delta = \text{Energy spread}$$

$$\text{If say, } \beta_{quad}\varepsilon_x << (\eta_x\delta)^2 \text{, then}$$

$$\sigma_{quad} = \eta_x\delta = \eta_x hz$$

“Skewed” maths

$$x_{quad} = \eta_x \delta$$

$$\delta = \text{ Energy spread} = hz$$

$$h = \text{ chirp}$$

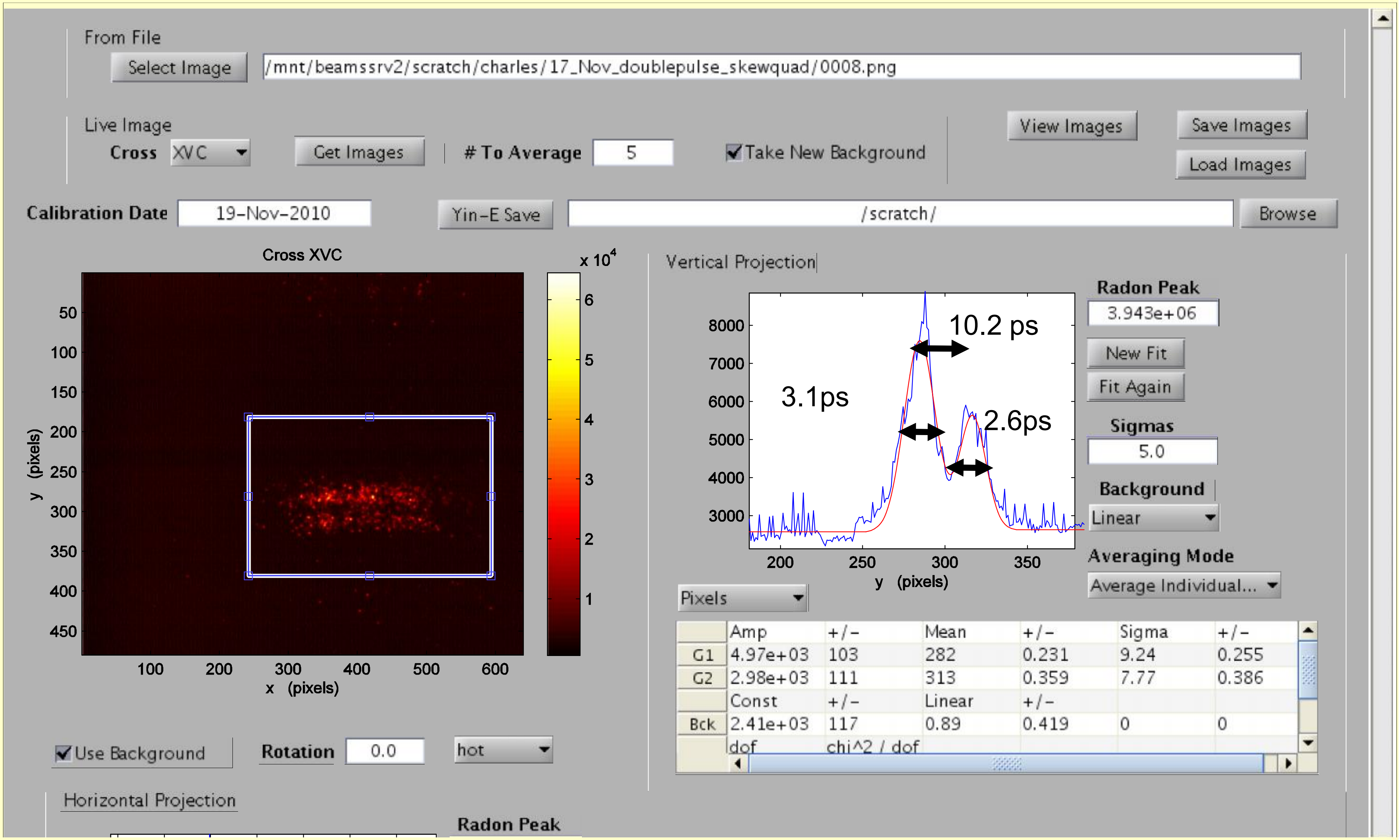
$$x_{quad} = \eta_x hz$$

$$\text{At the skew quad: } y' = \frac{x_{quad}}{f} = \frac{\eta_x h z_{in}}{f}$$

$$\text{Downstream: } y = R_{34} y' \propto z_{in}$$

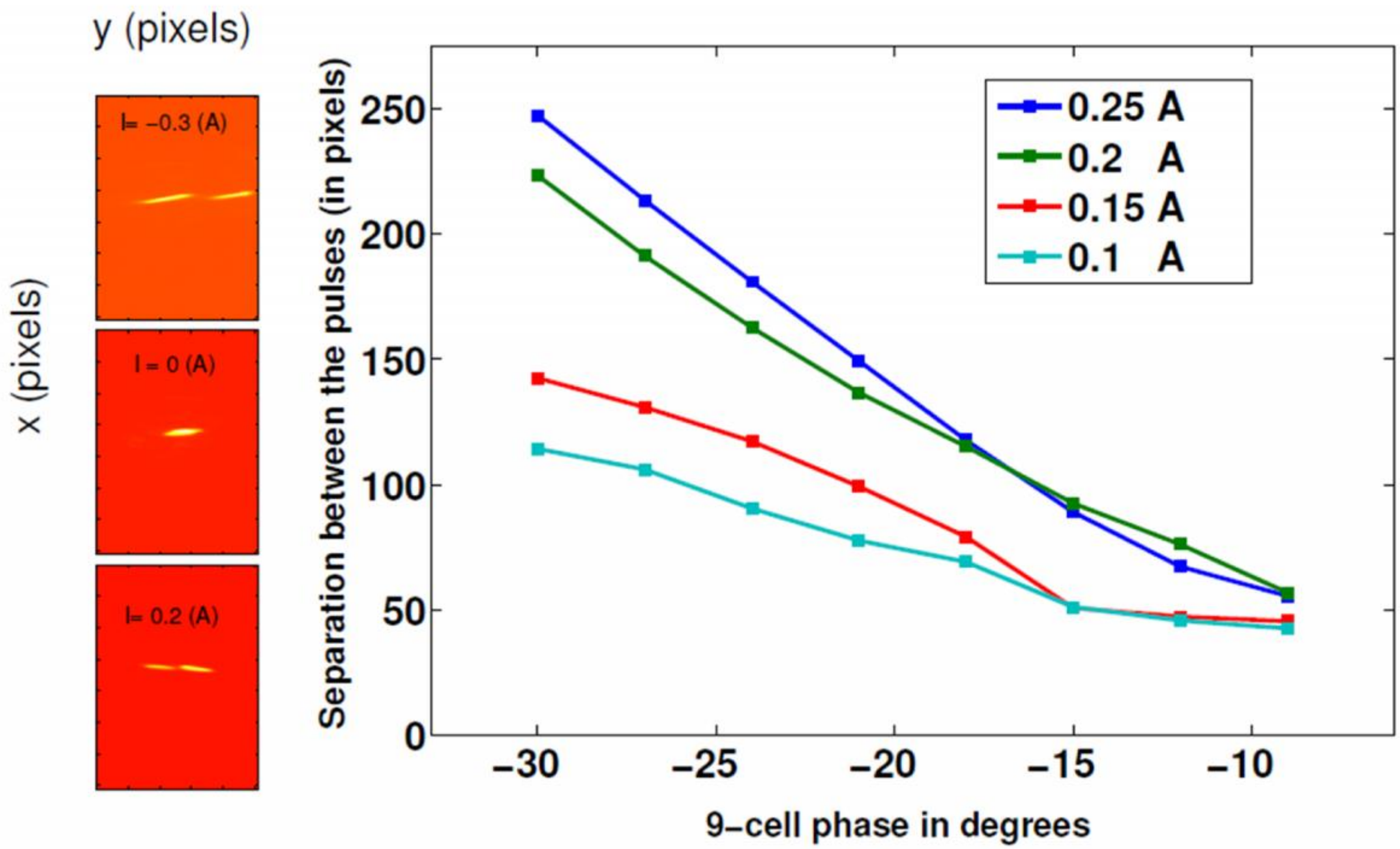
So, with skew quad on, (after cancelling x-dispersion), what we see on the screen is, $x \text{ vs } z_{in}$

Twin pulse

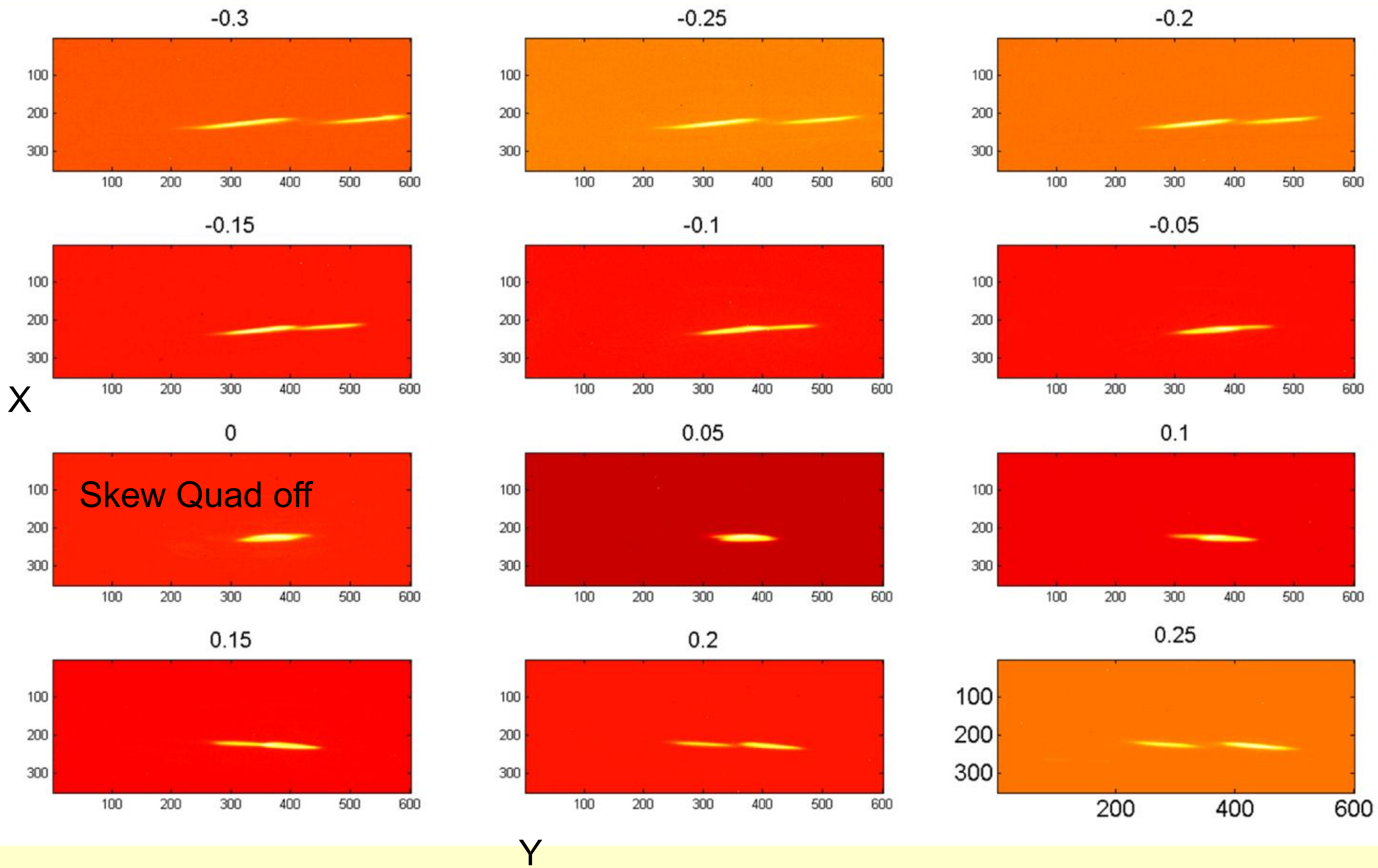


	Amp	+/-	Mean	+/-	Sigma	+/-
G1	4.97e+03	103	282	0.231	9.24	0.255
G2	2.98e+03	111	313	0.359	7.77	0.386
	Const	+/-	Linear	+/-		
Bck	2.41e+03	117	0.89	0.419	0	0
	dof	chi^2 / dof				

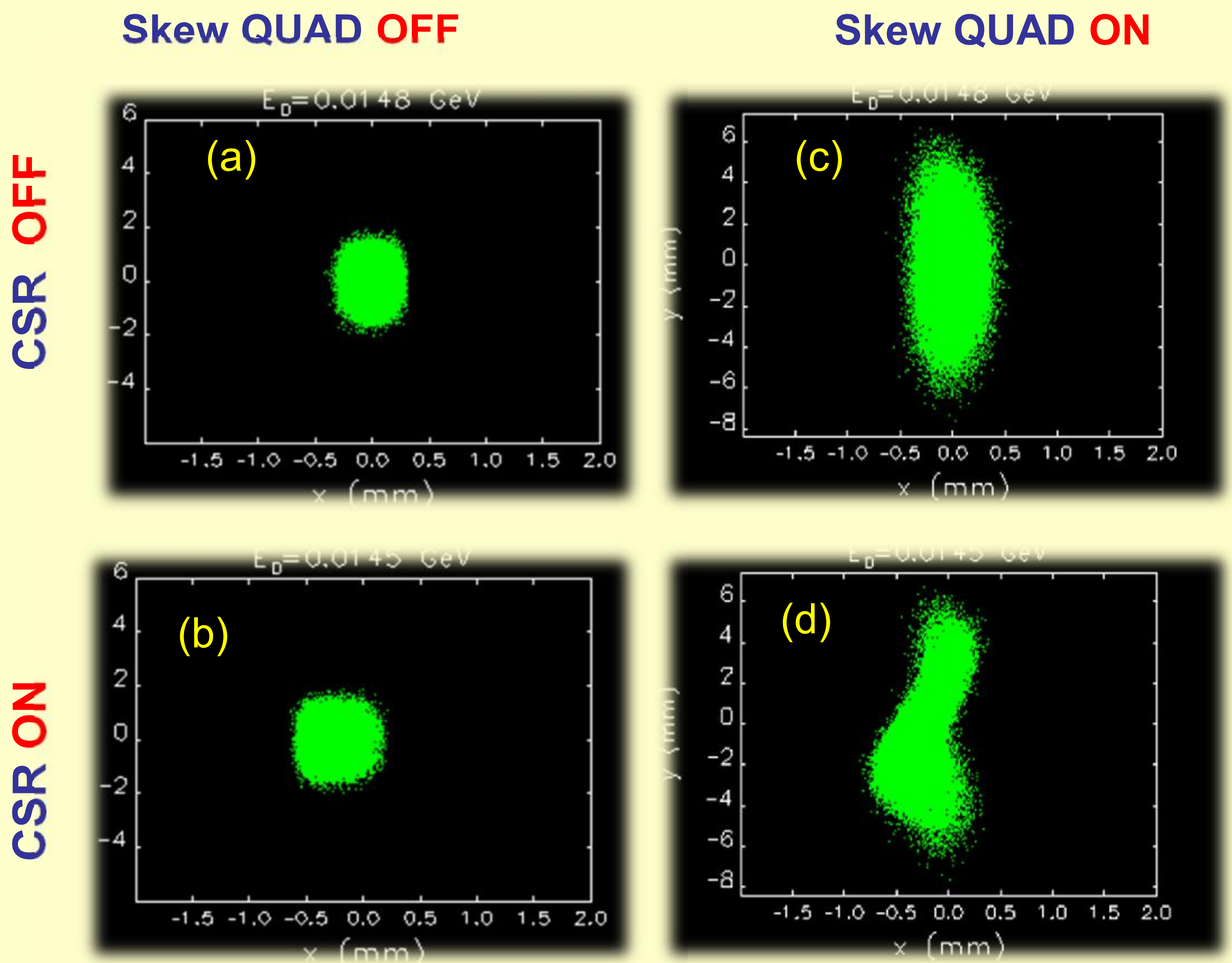
Twin pulse Profile @X24 vs SkewQuad



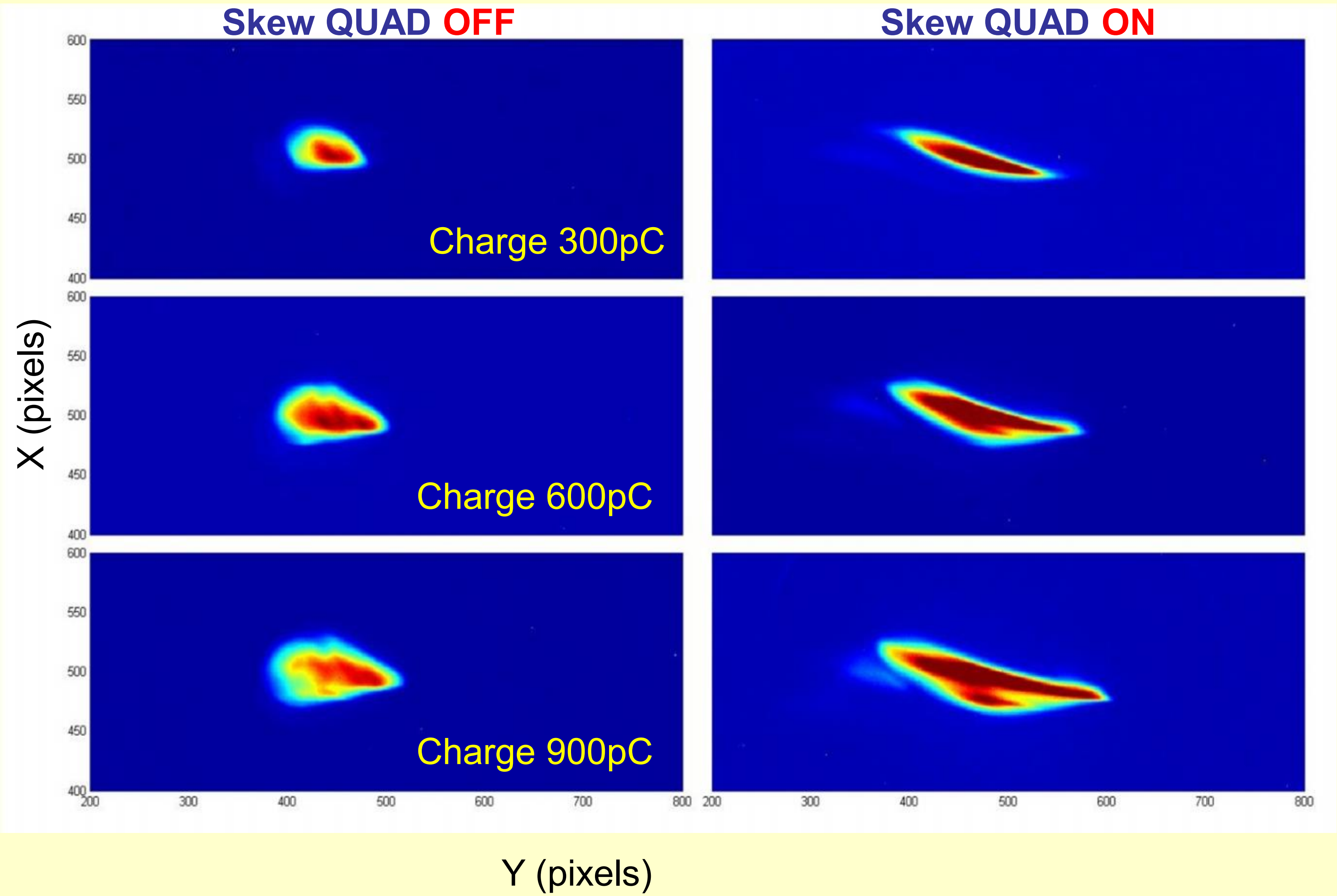
Twin pulse Profile @X24 vs SkewQuad



Skew quad diagnostic to resolve CSR effects



Skew quad measurements at X24



Operations

PRL **106,** 244801 (2011) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2011

First Observation of the Exchange of Transverse and Longitudinal Emittances

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An experimental program to demonstrate a novel phase-space manipulation in which the horizontal and longitudinal emittances of a particle beam are exchanged has been completed at the Fermilab A0 Photoinjector. A new beam line, consisting of a TM_{110} deflecting mode cavity flanked by two horizontally dispersive doglegs has been installed. We report on the first direct observation of transverse and longitudinal emittance exchange.

DOI: 10.1103/PhysRevLett.106.244801 PACS numbers: 29.27.−a, 41.75.Fr, 41.85.−p

$$\varepsilon_{x,\mathrm{out}}^2 = \varepsilon_z^2 + \left(\frac{17\lambda^2}{40D}\right)^2 \langle x'^2\rangle[\langle z^2\rangle + \alpha^2 D^2\langle\delta^2\rangle + 2\alpha D\langle z\delta\rangle]$$

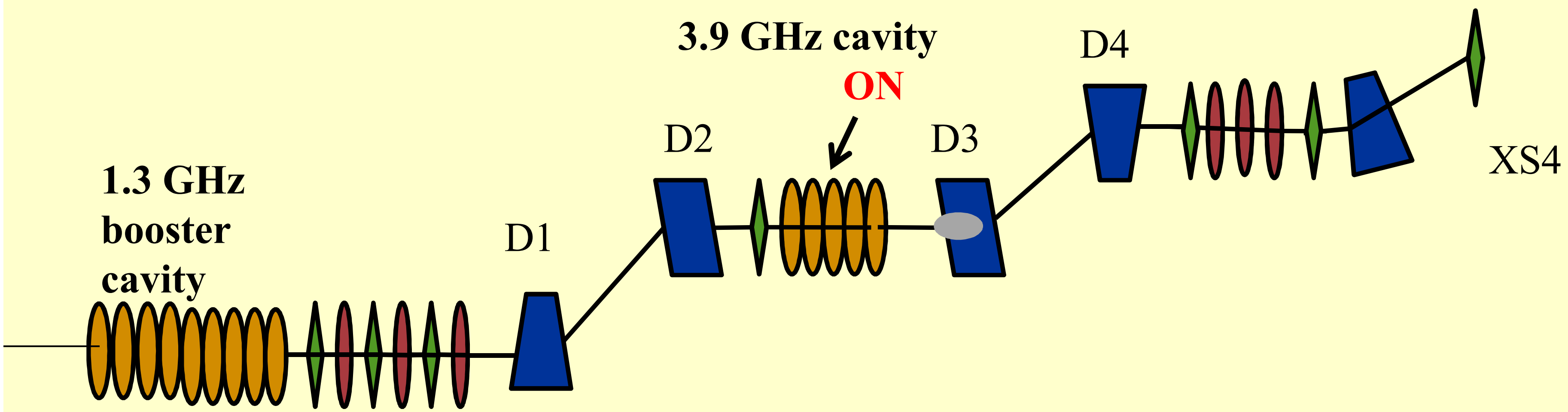
$$\varepsilon_{z,\mathrm{out}}^2 = \varepsilon_x^2 + \left(\frac{17\lambda^2}{40D}\right)^2 \langle x'^2\rangle[\langle z^2\rangle + \alpha^2 D^2\langle\delta^2\rangle + 2\alpha D\langle z\delta\rangle]$$

Nominal operation: Minimum energy spread

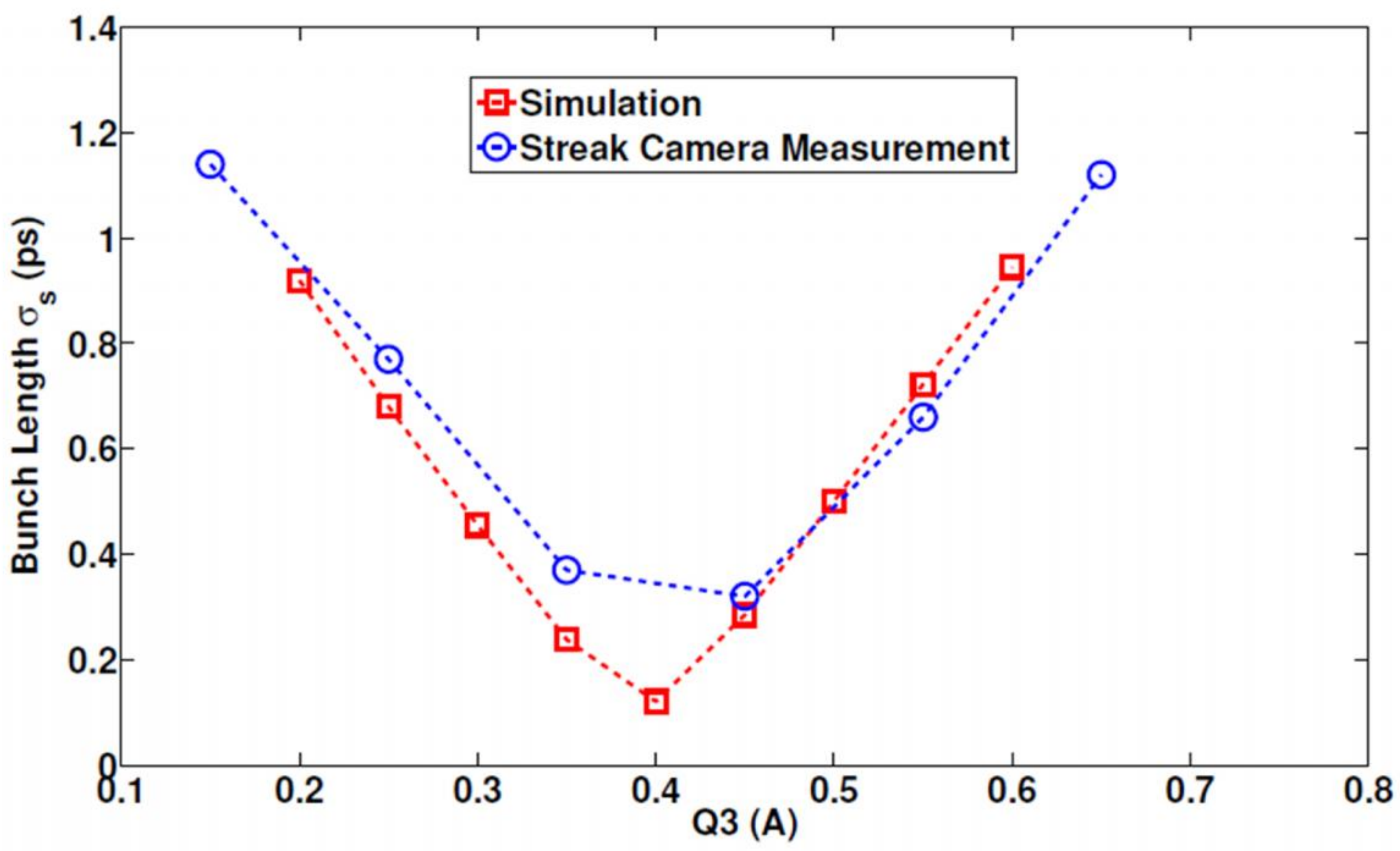
$$\varepsilon_{x,\mathrm{out}}^2 = \varepsilon_z^2 + \left(\frac{17\lambda^2}{40D}\right)^2 \langle x'^2\rangle[\langle z^2\rangle + \alpha^2 D^2\langle\delta^2\rangle + 2\alpha D\langle z\delta\rangle]$$

$$\varepsilon_{z,\mathrm{out}}^2 = \varepsilon_x^2 + \left(\frac{17\lambda^2}{40D}\right)^2 \langle x'^2\rangle[\langle z^2\rangle + \alpha^2 D^2\langle\delta^2\rangle + 2\alpha D\langle z\delta\rangle]$$

Pick 9-cell phase to cancel this term.
If 9-cell phase is -1/R_{56} , this term will vanish

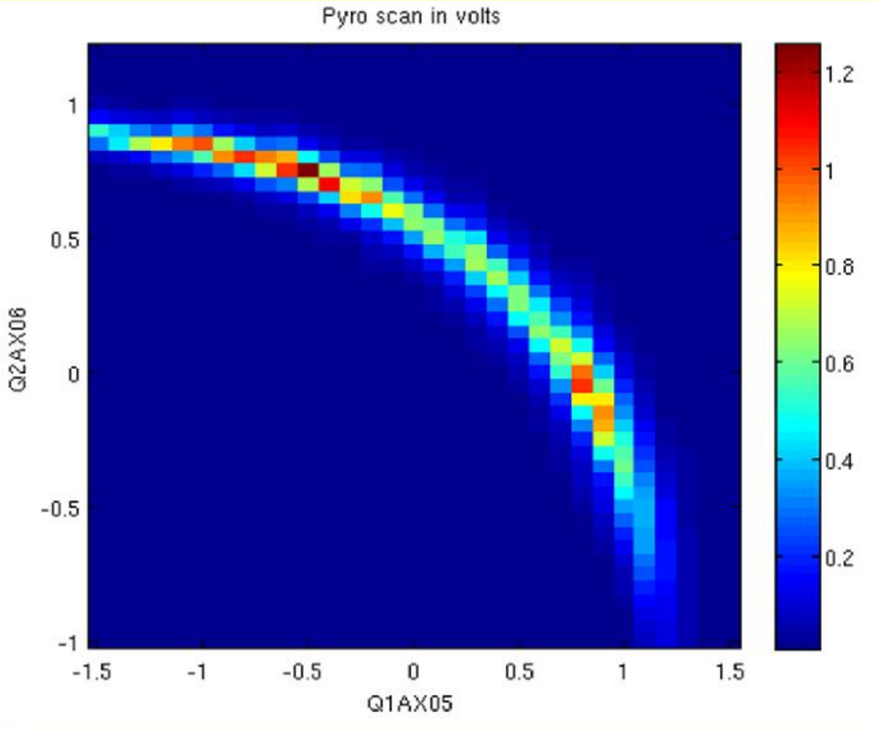


Chirp and Streak camera

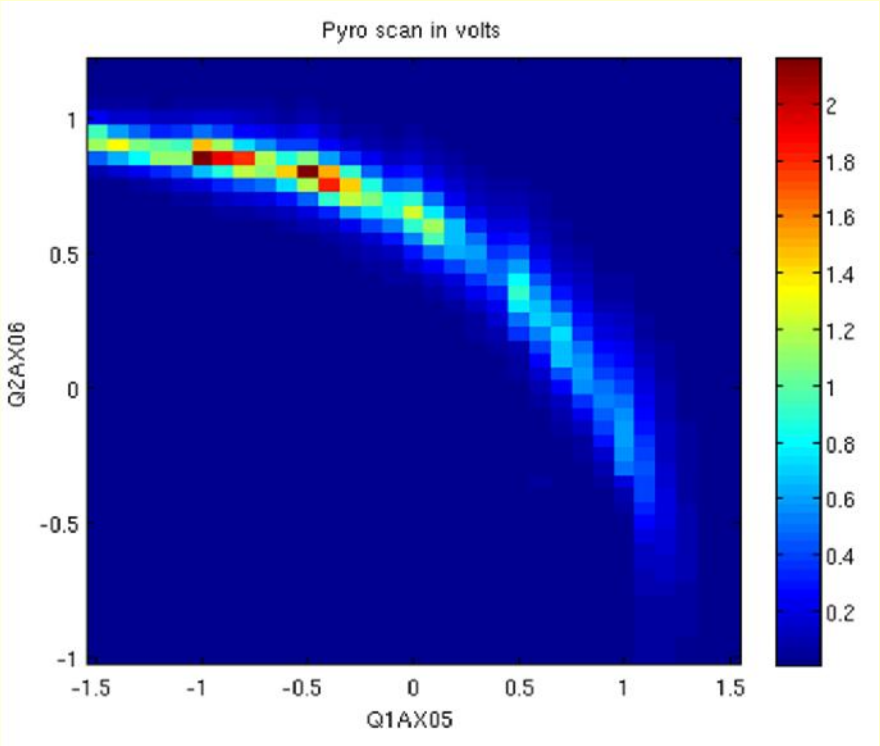


Pyroscan with and without RF chirp

No chirp

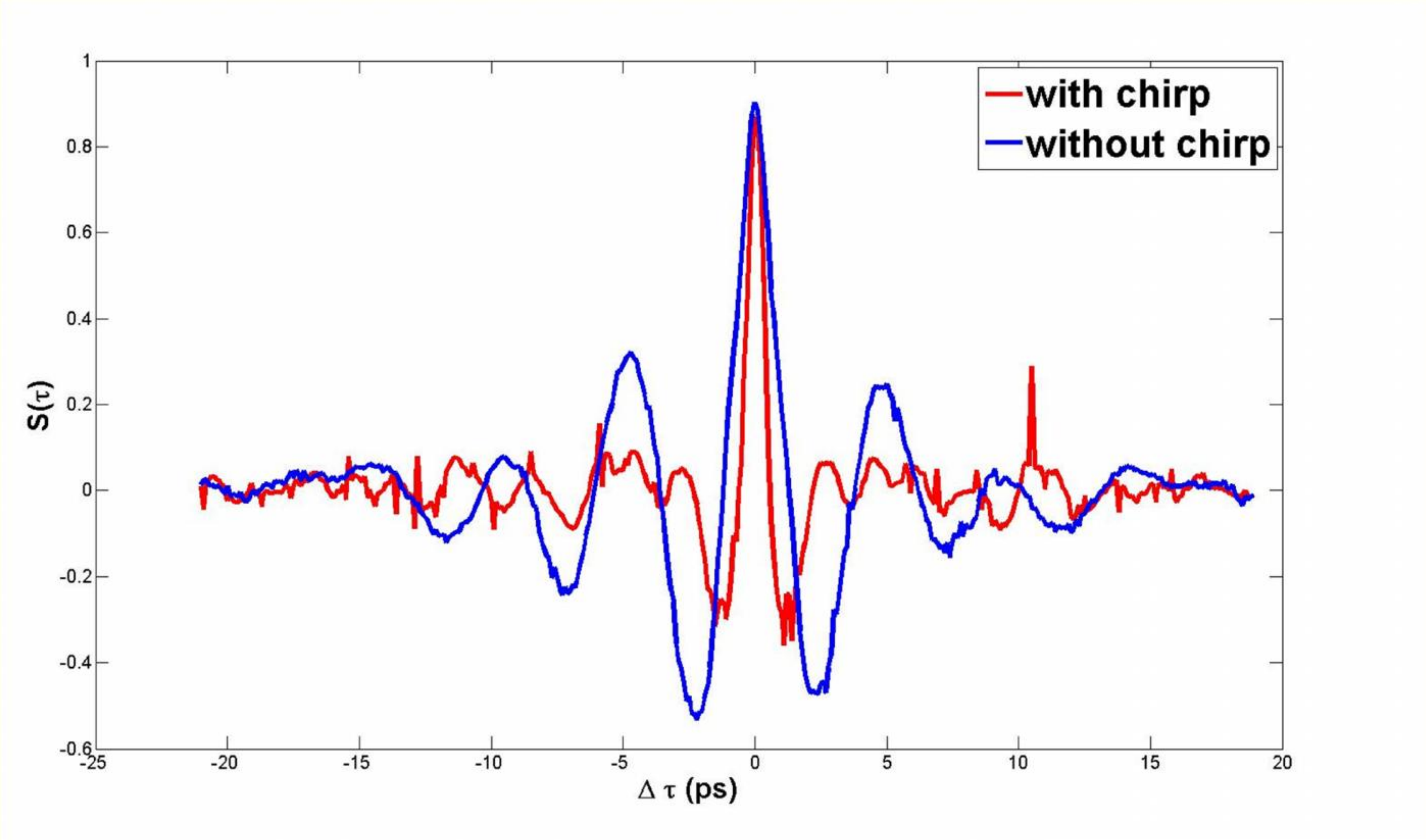


Chirp



- Signal increases ~ by a factor of 2

Interferometer measurement



Bunch length reduction ~ 2

Summary

- Coherent synchrotron radiation has been measured at A0 for various different charges
- Power, polarization and angular distribution of CSR have been measured. CSR diagnostics.
- Skew quad has been used to look at CSR effects.
- ‘Chirp mode’ with EEX shows pulse compression. Operational for diagnostics testing.

Thanks to…

- Randy Thurman-Keup
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- Alex Lumpkin
- James Santucci
- Helen Edwards
- Mike Church
- Philippe Piot
- Yin-E Sun
- Timothy Maxwell
- All the A0 techs….


CCTS-2
CCTS-3

Few references

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